THE EFFECTS OF HIGH ALTITUDE

EXPLOSIONS

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There have been seven artificial radiation belts made by the explosion of high altitude nuclear bombs since 1958: These artificial belts result from the release of energetic charged particles, mostly electrons, from the nuclear explosions. These seven explosions are:

Explesion	locale	time	<u>yield</u>	altitude
Argus I	South Atlantic	1958	1 kt	300 miles
Argus II	South Atlantic	1958	1 kt	300 miles
Argus III	South Atlantic	1958	1 kt	300 miles
Starfish	Johnson Island Pacific Ocean	July 9, 162	1.4 Mt	400 kg
USSR <sup>(1)</sup>	Siberia	Oct.22,162	soveral hundred kt	?
USSR	Siberia	0ct.28,162	?	?
USSR	Siberia	Nov. 1, 162	?	?

The Argus explosions of 1948 were carried out to study the trapping of energetic particles by the earth's magnetic Nicholas Christofolis, a physicist at the Lawrence

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The U.S. explosions Teak and Orange in the Pacific (below eight km) in 1958 may have injected some particles but the effects here were small and short-lived. Another reported USSR high altitude explosion of 1961 may to produced some effects but this is uncertain.

Radiation Laboratory, had for some time before Argus worked on Project Sherwood - the attempt to make controlled thermonuclear reactions in laboratory containers. To contain the intensely hot material used in Sherwood experiments no walls can be used. They would melt. Magnetic fields are used - shaped into "magnetic bottles" to contain the particles. Such a bottle as that used in Fig. 1 has been used successfully to contain hot electrons and protons for short times. The particles eventually leak out of the magnetic bottle, mostly through the ends, but they are contained for a time. Christofilos took this idea for a laboratory-size magnetic bottle and expanded it to earth size. He suggested that the earth's magnetic field should be able to contain and trap energetic particles and showed that a nuclear explosion would be a reasonable source of particles to populate the terrestrial bottle. (2) suggestion led to the Argus experiments.

Theplanning for Argus was well underway before the discovery by Van Allen of the natural radiation belt. In the Argus planning sessions it had been suggested that a natural belt might exist around the earth, which was of course borne out by the Explorer I and Explorer III satellites. After each of the Argus explosions, trapped particles were observed by Van Allen on the Explorer IV satellite. (3)

The Starfish explosion of July 9, 1962 was of higher yield than Argus and made not only a more intense artificial belt but a considerably more extensive belt. This belt is

of longer life than the Argus belts because it is at a lower latitude.

The three Soviet explosions of 1962 made artificial belts somewhat less intense than Starfish. These also were at high enough latitude so that they decayed rather rapidly. These three belts had different spatial extents maybe indicating different altitudes for the explosions.

## 4

### A Bomb as a Source of Charged Particles

"What is there about a nuclear explosion that makes an artificial radiation belt? The radiation belts, both natural and artificial, are simply large populations of charged particles trapped by the earth's magnetic field to stay for long times near the earth. The natural belts are made up mostly of energetic electrons and protons plus small numbers of deuterons and tritons and possibly some alpha particles and positrons as well. The artificial belts are made up mostly of electrons with some protons and maybe some of theother particles too.

There are two kinds of nuclear explosions, fission and fusion. The basic element of a fission reaction is the capture of a neutron by a heavy element, frequently U<sup>235</sup>, which then fissions, or splits, into two lighter nuclei or fission fragments. (4) In this process two or three neutrons are given off, of which about one per event may escape from the fissioning system. The neutron can produce trapped particles by decaying into a proton and an electron. At the time of fission several Y rays of roughly 1 Mev each are given off. These might produce some trapped electrons as the result of Compton scattering on air atoms but the trapped flux of electrons produced by this process is probably small enough to be neglected. Some particles are also given off by ternary fission. About one in 300 fission \$
produces an 
particle of from 5 to 25 Mev. It is uncertain

whether any of these & particles will get out of the fissioning system before they are slowed down to rest, but some of them may wind up trapped. (5)

After the fission process is over more charged particles are off. The fission fragments produced are unstable (they are neutron rich) and they decay by emitting electrons to become stable. One fission fragment emits about six electrons to become stable. These electrons are the most important source of all the artificial belts produced. They have energies up to about 8 Mev with an average energy of about 1 Mev. They can be released a long distance from the bomb because the fission fragment decay process is relatively slow. About one electron is given off in the first second after fission and then the other five are given off with a decay low

 $N_e = N_e(o) \tilde{\lambda}$  where t is in seconds So electrons are still being given off minutes to hours after the explosion. If the fission fragments expand with a velocity of about 500 km/sec, electrons can be liberated up to  $10^6$  km away from the explosion site. But probably the expanding fission fragments are mostly ionized (6) and they will be trapped by the earth's magnetic field and can not get nearly this far away from the explosion.

There may also be some positrons given off by radioactive debris after the explosion. One process that would cause this would be (n, 2n) reactions, for example:

(6)

The nucleus Al<sup>2</sup> decays by positron emission. This probably is not a very important particle source.

A fusion bomb works by burning hydrogen to make helium. The end products are not radioactive but some intermediate steps in the reaction produce charged particles that can be trapped. Deuterium and fritium are involved in the fusion process. Some tritons may be left after the reaction but they probably are of quite low energy and are not interesting as far as radiation belts are concerned. Neutrons are produced by both (d,d) reaction and (d,t) reactions. The neutrons from (d,d) reactions are of about 3 MeV and those from (d,t) reactions are of lh MeV. When these neutrons decay they make electrons and also protons of 3 or 14 MeV too, but as we shall see, the yield of this reaction is quite small.

A fusion or hydrogen bomb explosion will produce a quite insignificant artificial radiation belt compared to fission or atom bomb explosion of the same yield. The electrons from fission fragment  $\beta$  -decay are the most important source of particles for artificial radiation belts.

#### The Neutron Source

One of the sources of the artificial belts is neutrons given off by the explosion. We can evaluate how important this source is.

About  $10^{24}$  neutrons are given off by a one kiloton explosion. The neutrons are neutral and are therefore not trapped by the field but they are radioactive and decay by the reaction  $n\rightarrow e+p+\sqrt{2}$ . The decay produces electrons and protons which can be trapped. The antineutrino  $\sqrt{2}$  is of no interest to us here. The neutron mean life  $\sqrt{2}$  is 1000 seconds. The neutrons from fission are made with energies of about 1 MeV or a velocity  $\sqrt{2}$  of about  $10^9$  cm/sec. They travel about 50,000 km to get out of the magnetosphere. A fraction of them will decay inside the magnetosphere given by

$$f = \left(\frac{1}{1000}\right)\left(\frac{5\times10^{3}}{10^{9}}\right) = .005$$

Large enough charged particle fluxes will be made here to be important. The fraction of neutrons that decay will be larger for the slower neutrons.

The electrons that are made by decay have energies up to .78 Mev with a peak in the spectrum at about .30 Mev. The electrons' energy is very nearly independent of the neutrons' mergy. The decay protons, however, have energies nearly equal to the energy of the parent neutrons. This means that the protons from fission neutrons will be about 1 Mev. The proton flux from Starfish was probably about

10<sup>1</sup> protons/cm<sup>2</sup>/sec of E > 1 Mev. The natural proton fluxes are considerably larger than this in most regions of space so we can ignore the neutron decay protons. The neutrons from the (d,t) reactions of the fusion bomb have 1½ Mev protons. There will not be many of these made. The 1½ Mev neutron velocity is a factor of four larger than 1 Mev neutrons so the fraction of them that decays is only  $\frac{1}{4}$  of the 1 Mev neutron decays. This means that for Starfish the 1½ Mev proton flux will be less than  $10^{14}/\text{cm}^2/\text{sec}$ . However, the neutron decay electron flux is considerably higher than this. (7) If M neutrons are given off by an explosion on the equator, the total neutron flux F at an observation point (see Fig. 2) will be  $\frac{M}{4\pi}$ 

where  $\rho$  is the distance from the explosion point to observation point.  $\rho = \sqrt{+R^2 - 2Rr \sin \theta}$  cos  $\phi$ The neutron decay density from this flux will be

$$N_0 = \frac{M}{4\pi \rho^2 \sqrt{T}} \frac{\text{decays}}{\text{cm}^3}$$

The explosion is a point source but the particles will spread out in longitude by drift to form a shell. We can average the decay density in longitude

$$\overline{N}(V,\theta) = \frac{1}{\pi} N_0 V, \theta, \phi d\phi = \frac{M}{2\pi^2 r} \int_{V+R^2-2R r \sin \theta \cos \phi}^{\phi}$$

This space-averaged neutron decay density can be transformed directly to be an electron omnidirectional flux distribution in space.

If we have a neutron source above the atmosphere we must consider not only neutrons traveling upwards away from the explosion but albedo neutrons from the top of the atmosphere. About 80 percent of the downward traveling neutrons will be reflected from the atmosphere and then travel upwards. In the reflection process the neutrons will be partly thermalized by collisions with air nuclei. As a result of this the rate of decay of these neutrons will be higher and actually more total decays will result from the initially decard moving neutrons than from the upward moving ones. Carrying out these calculations and normalizing crudely to the Starfish explosion we get the spatial distributions of electrons shown in Fig. 3. calculations have been made with and without albedo and the importance of albedo in Fig. 3 is obvious. Electron fluxes up to about 10 electrons/cm2/sec are expected from neutron decay from Starfish. These are initial fluxes and will, of course, decay with time. This flux is not negligible but it is concealed by the considerably larger flux of fission electrons.

#### Rarbicle Motion

We need to understand the motion of charged particles in a magnetic field in order to understand how an artificial bolt of particles surrounding the earth is made from a point source emplosion. For the particles we are interested in we can break this motion down into three components (see Fig. 4)

- (a) a rapid gyration of the particles around the field line.
- (b) a bouncing back and forth along a field line from one hemisphere to the other.
  - (c)a slow drift in longitude around the earth.

The gyration period or cyclotron period of an electron in the carth's field is roughly a microsecond. The bounce period is of the order of one second.

It is essential to understand the phenomena of bouncing to see how a radiation belt can exist. Whenever a grating charged particle moves into a converging magnetic field there is a force produced that tends to push the particle out of the converging region. This force is

where V<sub>g</sub>is the component of the particle's velocity around the field line and B<sub>V</sub> is the component of the magnetic field property to the axis of symmetry (B<sub>r</sub> = 0 for a uniform field). The force P is always directed out of the region of convergence.

Law each end of one of the earth's field lines the field converges towards the surface of the earth, therefore the force P acts like a restoring force which tends to push the particle along the field line towards the equator. As a

result, a bouncing motion takes place much like the oscillation of a pendulum. This bouncing motion takes place with a magnetic moment & of the particle a constant of the motion. The magnetic moment is defined by

$$M = \frac{E_{\perp}}{B} = \frac{\sum_{i=1}^{n} w_{i}^{2}}{B} = \frac{\sum_{i=1}^{n} w_{i}^{2} \cdot w_{i}^{2}}{B}$$

where E is the particle's kinetic energy associated with the gyration and  $\propto$  is the angle between V and B called the pitch angle. A static magnetic field does no work on a particle so V = constant and because A is a constant we have  $\frac{1}{\sqrt{q_2}} \propto = constant.$ 

During the bouncing motion & changes as B does, according to this equation. The particle turns around when  $\sin \propto = 1$ or at a magnetic field strength  $B_m$  given by  $\frac{2m^2\alpha}{R} = \frac{1}{R_m}$ 

This point of field Bm is called the particles mirror point. A particle's mirror point depends only on its initial pitch angle  $\ll$  (not on its energy). If the value of  $B_{m}$  for a particle is below ground level or in the dense atmosphere this particle will be lost right away.

The particles also drift in longitude around the earth. Thore are two effects that produce this drift. The radial gradient of the magnetic field and the curvature of the field limos both act to make the electrons drift east and protons west. The field gradient effect can be understood by considering the gyration of the particle around the field line. Because

of the field gradient, the cyclotron radius is larger on the high altitude side of the line. This assymmetry in the symmetry causes the particle to move sideways as shown in Fig. \_\_\_\_\_. Particles with higher velocity drift faster in longitude. A fission electron takes about one-half hour to drift around the earth. As the particle drifts in longitude it moves from one field line to another. Which now field line the particle moves to is determined by the fact that

$$I = \int co_{2} \times dl = \int \sqrt{1-B/B_{m}} dl$$

is a constant of the motion (where the integral is taken along a field line from one mirror point  $B_m$  to the other  $B_m$ ). Actually I is only an adiabatic constant of the motion. If B changes in a time short compared to the bounce time, then I in not a constant. The magnetic moment  $\mu$  is also only an adiabatic constant of the motion.

The integral invarient I is a kind of weighted length of the field line between  $B_m$  and  $B_m$ . As the particle drifts from one field line to a new one the value of  $B_m$  at the mirror point stays constant because M is a constant of the motion. Also I remains constant during the drift so the length of the field line from  $B_m$  to  $B_m$  remains constant. As the particle drifts in longitude around the earth only one not of field lines will satisfy those constrainst and the

particle will return to the line it started on. McIlwqin has introduced a parameter L to label such a shell of field lines. In a dipole field L would be the distance from the center of the earth to the equatorial crossing of the field line in units of earth radii. The shell L = 2 would go to 6370 km altitude at the equator. For the real field of the earth, which varies considerably from a dipole, the definition of L is more complicated. However, the L = 2 shell still has an average equatorial altitude of about 6370 km although it varies about \$500 km from this.

We can now understand what happens to particles emitted at one point in space by a nuclear explosion. In a few seconds they are spread out along a field line and in a few hours they drift around the earth and spread out in longitude to form a blanket around the earth. The thickness of the blanket depends on the initial dimensions of the particle source.



#### Early History of Starfish

We now have an idea about what should happen to the particles from an explosion. Let us see what the observations say happened after the Starfish explosion of July 9.

Magnetic and EM signals and a whistler radiated by the explosion were observed at several places. (8, 9, 10, 11)

These may play a part in the artificial belt. They may interact with particles in the natural belt and either change their energy or scatter them and change their pitch angle.

These changes in the naturally trapped particles may produce some of the observed effects.

Just seconds after the explosion artificial aurora were observed in New Zealand. (12) These are produced by the electrons and other particles from the explosion that are not trapped. Lots of these particles have mirror points below the atmosphere. Because of this they will enter the atmosphere and interact with oxygen and nitrogen atoms. The excited atoms will emit light to form the aurora. Rockets have been flown into natural aurora and energetic electrons found, so this process of electrons making auroras is well established.

Just two seconds after the explosion increased ionospheric absorption of cosmic radio noise was observed in Alaska (13) at  $L\sim 6$ . This is probably due to debris from the explosion traveling upwards to these field lines releasing electrons  $\beta$  -decay some of which promptly are lost into the atmosphere.

The increased ionospheric electron densities produced would this way enhance the cosmic noise absorption. The peak absorption was detected within one minute after the explosion followed by recovery to normal in a few hours. Attenuation like this was not observed in the U.S. at the same distance as Alaska or in the auroral region in Canada or Norway so the effect is clearly associated with early time effects of charged particles from the explosion.

A few minutes after the explosion increased f<sub>min</sub> was observed on an ionosonde in Jamaica (14) indicating increased absorption in the lower regions of the ionosphere. This must have been due to trapped electrons drifting east and some of them getting lost as they go.

Topside soundings of the ionosphere on Ariel (15) also showed increased electron densities in the ionosphere above the F<sub>2</sub> layer shortly after the explosion.

There also will be increased electron densities in the region near the explosion due to absorption of soft X-rays from the explosion (as much as half the energy of the explosion may be in the form of these soft X-rays). But this effect will only be line of sight from the explosion and this effect cannot explain the Alaska or Jamaica observations.

# (16)

#### Syncrotron Radiation

A few minutes after Starfish syncrotron radiation from the trapped electron was observed in Peru(17). This is the only effect of the artificial radiation belts that is observed on the ground for long periods. Syncrotron radiation is the electromagnetic radiation given off when an electric charge is accelerated in a circle. (18) It was first observed as light emitted from a syncrotron electron accelerator. the charged particles have V<< c then the radiation is emitted only at the cyclotron frequency and is called cyclotron radiation, but when the particle is relativistic then many higher harmonics of the cyclotron frequency are emitted too and the radiation is called syncrotron radiation. The radio emission of the planet Jupiter in the 30 cm range is tentatively identified as being syncrotron radiation from trapped electrons with energies in the order of 5-100 Mev. (19)

The total power radiated by a particle by syncrotron radiation is

$$P = \frac{2}{3} \frac{e^2}{c^3} \left( \frac{dv}{dt} \right)^2$$

An expression that is more useful in comparison with experiments is the power spectrum radiated in the electrons orbited plane for a relativistic electron (20)

$$P(f) = 4.1 \times 10^{-30} B \text{ F}(f) \frac{\text{watts}}{\text{opa ster}}$$

where B is the magnetic field strength in grams, Y is the relativistic energy factor  $\frac{E}{m_e c^2}$  and F(f) is a function of the frequency f. Evaluating P(f) at 50 mc for B = .16 gauss



and E = 2 Mev give  $P(f) = 4 \times 10^{-3}$  watts/cps-ster. Integrating P(f) over the electron spatial distribution and fission energy spectrum for Starfish and integrating over antenna patterns gave calculated sky brightnesses in very good agreement with those measured shortly after Starfish. (21)

Attempts were made to observe syncrotron radiation from the natural Van Allen belt but it could not be measured due to the background of other natural radio noises. After the Starfish explosion syncrotron radiation was observed by several stations. The Bureau of Standards has a radio observatory in Peru which contains about 20,000 dipoles. (17) This array can study the radio noise coming in a narrow angle from the zenith (which is very nearly the magnetic equator). The newly trapped electrons from Starfish produced more syncrotron noise than the natural belt electrons because there were more of them and they were of higher energy. The maximum 50 mc signal at Peru arrived at + 6 minutes after the explosion. This delay time is compatible with the time required for a 2.7 Mev electron to drift in longitude from the location of the explosion to Peru. A second peak was seen about 35 minutes later due to the electrons drifting around the world a second time. After this the noise was nearly constant because the electrons had dispersed in longitude due to their different velocities. Polorization measurements made at Peru with the dipole array show the radio noise received was roughly East-West linearly polarized as is expected for syncrotron radiation.

(18)

Several other antennas measured the syncrotron radiation after Starfish. (22) At Wake Island the maximum signal was obtained at + 25 minutes. This later arrival than at Peru shows that electrons drift east as expected. This delay time is right for about 2 Mev electrons.

Comparing several receiving stations shows that only stations within 25° of the magnetic equator detected syncrotron radiation. This is reasonable because the radiation is given off in the instantaneous direction of motion of the electron and this means that large signals should be found at the equator and the signal should decrease rapidly going off the equator.

Observations at Peru showed that the syncrotron noise decayed with a time behavior given by

$$n = n_0 \frac{1}{1 + \frac{\xi}{60}}$$

where t is the time in days after Starfish. This time decay is not representative of the decay of the artificial radiation belt as a whole because a large fraction of the syncrotron noise is given off by low altitude electrons where the magnetic field B is large. These low altitude electrons will be lost quite rapidly.

#### Satellite Data on Starfish

On July 10 there were four satellites in orbit that had electron detectors on board and which gave useful information on the newly trapped particles.

	apogee	perigee	inclination	detectors
ARIEL	1209 km	393 km	54°	shielded GM counter E <sub>e</sub> > 4.7 Mev
INJUN	1010 km	890 km	67°	shielded GM counter, counting several Mev electrons by Bremsstrah-lung
TELSTAR	5630 km	955 km	44.76	4 channel solid state detector E > .2 Mev
TRAAC	1110 km	951 km	32.4°	shielded GM counter E>1.6.Mev

The Injun satellite had been in orbit a long time, and so it provided a very good before-after comparison of the radiation belt. The TRAAC detector also showed a good comparison this way, as did Ariel. Unfortunately, the Telstar satellite was launched the day after Starfish, so it could not give a before-after comparison. This is quite unfortunate, because the Telstar satellite goes to high altitudes and maps out regions of space that are unavailable to the other satellites.

The joint US-UK satellite Ariel showed that high energy electrons resulting from the bomb appeared very shortly after the explosion at high latitudes - up to L = 5 or more. (23) Ariel went out of operation a week after Starfish, but during this time the flux of energetic electrons stayed high up to L = 5.



The TRAAC detectors followed the decay of low altitude Starfish electrons until it also went out of operation. (24)

TRAAC located a puddle of fission debris sitting on top of the atmosphere in the Pacific, continuously emitting electrons into the belt. (25) These new electrons from the debris puddle will have short lives, because they are emitted at low altitudes and thereforehave low mirror points and encounter a fairly dense atmosphere.

By comparing the measurements of the several different detectors having different energy responses, the energy spectrum of the new particles was determined. At about 1000 km the spectrum closely resembled a fission energy spectrum, thus identifying the decay of fission fragments as the major particle source. (26)

The Injun counters mapped out the new belt at 1000 km altitude and produced the first flux contour picture of the Starfish electrons. (27) The Telstar satellite produced all of the information above 1000 km for the first three months after Starfish. (28) The experimental data from Injun and Telstar for a short period after Starfish were organized and plotted. A comparison of this data is shown in Fib. 6. The region of highest flux for the Injun data is about 109 electrons/cm²/sec and for the Telstar data the highest value is also about 109 electrons/cm²/sec. The outer edge of both flux distributions shown is at a flux of 107 electrons/cm²/sec. These distributions in Fig. 6 are only approximate and involve some extrapolations in both cases. Also they

are not for the same time (Injun is plus 10 hours and Telstar is plus 5 days) but they still are fairly accurate and can be compared reasonably. It is obvious the Injun flux distribution is much more compressed than is Telstar's. The total number of particles found by integrating imside the Injun distribution is about 10<sup>25</sup> electrons (29) and inside the Telstar picture is about 10<sup>26</sup> electrons. (28)

This difference is reasonably well understood now. We will return to this point later.

A map of the Starfish electron fluxes at 400 km altitude above the earth is shown in Fig. 7. These are the fluxes as of one week after Starfish. They have decayed probably about a factor of 10 up to the present. The reason why large fluxes are seen in the South Atlantic and not elsewhere has to do with the earth's magnetic field. The field is weakest here so electrons, in order to satisfy the condition of mirroring at a certain value of B<sub>m</sub>, must come closest to the earth in this region. Therefore the largest flux is seen in this region.

The spatial distribution of electrons from Starfish is not easy to understand. The ionized debris from an explosion will expand outwards and because the debris will be a good conductor it will push the magnetic field ahead of it. In this way a bubble will be blown in the magnetic field. (30)

The bubble will stop expanding when the energy in the excluded field equals the initial kinetic energy E of the debris.

$$E = \frac{B^2}{8\pi} V = \left(\frac{B^2}{8\pi}\right) \left(\frac{4\pi R^3}{3}\right) = \frac{B^2 R^3}{6}$$

The bubble will collapse and leave behind a region about the size of the bubble filled with fission fragments and electrons. For the Argus explosion  $E \sim 1 \text{ kt} = 4 \times 10^{19} \text{ ergs}$ . For B = .3 gauss we get

 $R \approx 100 \text{ km}$  measureThis is the approximate thickness of the Argus electron shells. (3)

But this simple model does not work for Starfish. The radius here would be  $R \approx 1000$  km but actually the debris must have gone considerably further than this. In order to get to L=5, the bubble would have to be about twice this diameter if it grows across field lines or even larger if it grows upwards. The bubble might break up into several bubblets to allow the electrons to disperse more.

Several satellites launched after Starfish have made measurements on the artificial belts and confirmed the general picture of the electron flux distribution. A magnetic spectrometer flown on the Air Force satellite 1962 \( \beta \) K measured the electron energy spectra at different L values. Such spectra for Dec. 8, 1962 are shown in Fig. 8. At L = 1.25 the energy spectrum looks like thefission spectrum

(Curve A, Fig. 8) except that there are fewer low energy electrons. These low energy electrons probably have been lost by coulomb scattering between July and December. The measured spectrum at L = 1.57 is softer. It has considerably fewer high energy electrons than a fission spectrum. Not much decay has taken place here so this spectrum should be quite like the initial spectrum on July 9 at L = 1.57.

This information on the energy spectrum helps in understanding the difference in the Telstar and Injun flux distributions in Fig. 6. In developing these flux distributions it was assumed that all the electrons involved had a fission energy spectrum. The Injun detector does not count electrons of E < 2 Mev efficiently. The Telstar detector does count low energy electrons with E < 1 Mev well. This means that Telstar will count the soft electrons at L = 1.57 much more efficiently than will Injun. Because of this, the Injun contours should close at lower altitude than the Telstar contours. These two sets of contours are two different pictures of the same thing. The Injun picture shows the spatial distribution of electrons of E  $\sim$  3 Mev. The Telstar picture shows the spatial distribution of E~ Mev electrons and probably gives a better estimate of the total artificial belt electron population than the Injun estimate because Injun does not include the large number of low energy electrons present.

Several satellites have followed the decay of the Starfish electrons. We will consider this in a later section.

#### Radiation Damage

The artificial radiation belt can cause damage to radiation-sensitive components such as solar cells and man. The same, of course, is true of the natural radiation belt. The power supplies of three satellites were damaged by the Starfish electrons. The Ariel satellite stopped transmitting data after about one week, and the TRAAC and Transit 4B satellites stopped in about one month. The solar cells on these satellites were progressively deterioratent due to the artificial electrons from Starfish. The output voltage of a solar cell goes down as the radiation exposure goes up, (32) as shown in Fig. 9. A normally designed satellite power supply will malfunction if the solar cell output drops to about 80 percent of its designed value. From Fig. 7 we see this will take about 101 electrons/cm2 for the P-on-N type solar cells used on Ariel. Ariel stays in the high flux region of 109 electrons/cm<sup>2</sup>/sec about 10 percent of the time so it encounters roughly 1012 electrons/cm2/day. so a week is about the right time for the power supply to last before going into undervoltage. The output from the solar cells on TRAAC and Transit LB was monitored (33) and the time history is shown in Fig. | D. The initial slow decrease is due to the natural trapped particles, and the sudden change on July 9 is clearly due to the trapped electrons from Starfish. Telstar has a different and more radiation-resistant N-on-P type solar cells, and it lived a long time in the artificial

radiation belt. Injun also lasted a long time after Starfish because its power supply was designed so that it could stand a larger percentage degradation and therefore more radiation. Satellites can clearly be designed to have long lives in the Starfish belt, or even more intense belts, but Ariel, TRAAC and Transit 4B were not expected to encounter these radiation levels, so they were not designed for it.

A total flux of 3 x 10<sup>7</sup> particles/cm<sup>2</sup> is equivalent to 1 Rad (if the charged particles are minimum ionizing). The flux of natural high energy protons is about 2 x 10<sup>1</sup>/cm<sup>2</sup>sec. This will result in about 12R/hour radiation dose to a lightly shielded person. The high electron flux region from Starfish has about 10<sup>9</sup> electrons/cm<sup>2</sup>/sec. This would result in about 30 R/sec. Shielding can be used to reduce the radiation dosage. For a fission energy spectrum, 1 gm/cm<sup>2</sup> of shielding material will reduce the dose about a factor of 10, 2 gms/cm<sup>2</sup> a factor of 100, and 3 gms/cm<sup>2</sup> a factor of 1000. But it is quite difficult to reduce the radiation by more than a factor of 5000 because of the X-rays produced by the electrons hitting the shielding. The fraction f of the electrons energy that goes into bremstrahlung is about

$$f = \frac{ZE^2}{1600}$$

For fission electrons incident on an Al shield  $f\sim.01$ . The absorption length of the bremstrahlung X-rays is about 20 gms/cm<sup>2</sup> so the rate of energy loss is about a factor of 50 less than for minimum ionizing charged particles.

Combining these factors we get a reduction of a factor of 5000 in the rate of energy deposition under the shield. But the X-rays that are produced, having an absorption length of 20 gm/cm<sup>2</sup> are very hard to absorb out so additional shielding after about 4 gms/cm<sup>2</sup> does not help much.

With a factor of 5000 reduction in radiation due to shielding the radiation dose from the Starfish flux would still reach about 20 R/hr. About 500 R is lethal to most people so this region of space cannot be used for prolonged manned space flight.

Attention was given to the problem of manned flight shortly after Starfish. The flux map for one week after Starfish was used to calculate that about 1 R radiation dose would be received by an astronaut on a six-orbit mission at that time. (26) By the time the MA 8 flight took place, decay of the trapped particles had reduced the expected dose considerably, and the dose received was well under 1 R. This is less than is received in some chest X-rays and is not a problem.

## Effects on the Natural Radiation Belt

The question had been raised before Starfish as to whether the explosion would seriously alter the natural Van Allen belt. Most opinion was that it would not. Because of the large flux of artificial electrons injected by Starfish it is not possible to say anything about changes to the natural belt electrons. But there is some information about the high energy proton fluxes. Nuclear emulsions flown on recoverable satellites measured the 55 Mev proton flux at various times before and after Starfish. (37) About three weeks after Starfish the 55 Mev proton flux at 400 km was about a factor of 5 larger than before Starfish. It has decayed since then. There is some uncertainty about the rate of decay of the protons but the decay constant is of the order of 107 seconds. There is no source of 55 Mev protons from the explosion so these particles must be natural belt protons. Very likely the explosion displaced a small fraction of the high energy Van Allen belt protons. The hydromagnetic wave from the explosion might do it but the details of such a process are not understood quantitatively.

If only a few percent of the high energy protons at high altitudes were moved downwards this observation could be explained. The high energy proton flux at high altitudes has not been changed measurably by the Starfish explosion.

And Telsian

Measurements on Explorer XV before and after the USSR explosions on Oct. 28 and Nov. 1 show no measurable change in the energetic proton flux. (38)39)

## The Soviet High Altitude Explosions

On October 27, 1962, NASA launched the Explorer XV satellite to study the artificial radiation belt. But before it got in the air there were two artificial belts and by the time it was up for a day there was a third belt. The Soviets conducted to high altitude explosions on October 22 and October 28 and then a third one on November 1. Explorer XV had electron detectors on it to cover the range of energies expected for fission electrons, detectors with thresholds from \( \frac{1}{2} \) Mev to 5 Mev. Fig. | shows the distribution of electrons for two of Brown's threshold detectors (40) on Explorer XSV. Curve A and C were taken just after Explorer XSV was launched and curves B and D were about 5 hours later after the second Soviet explosion. The new belt of electrons from the explosion is clearly evident starting at L = 1.8 and extending out to about L = 3. The inner edge of the new belt is quite sharp, perhaps indicating expansion of the debris from the explosion preferentially upwards as in a field free bubble. Inside about L = 1.7 the electron fluxes were essentially unchanged by the Soviet explosions. The little bump on curve A of Fig. | at L ~1.8 is probably residue from the Soviet explosion of October 22. This explosion was detected also by Telstar. (39)

The polar-orbiting Air Force satellite 1962 ß K carried several radiation detection instruments to study theartificial belts. The five-channel magnetic electron spectrometer (34) on this vehicle measured electrons of energies 0.3 to 3.2 Mev. This instrument detected the October 28 Soviet explosion and

and found that at about L = 1.9 the electrons had roughly a fission spectrum but at higher L values the spectrum became softer. It would appear from this that the explosion site was at about L = 1.8 and the higher L electrons were softened maybe in the same way that the Starfish electrons were. The Explorer XV detectors also indicate that the energy spectrum of the electrons introduced by the Soviet October 28 explosion became softer with increasing L. (40)

Several directional detectors on 1962  $\beta$  K showed that the electrons injected on October 28 had a flux distribution appropriate to a sonce well off the equator. (41) This is what we would expect for an explosion at a few hundred kilometers altitude. Detectors on 1962 K measured the time history of the artificial belt of October 28 and then detected the injection of new electrons in a rather limited new belt at about L = 1.8 on November 1. In both cases the flux of the new particles decreased with time constants of a few days and the low energy particles seemed to disappear faster.

About a week after the Soviet explosions, the particles injected at L > 1.7 have decayed some. The spatial distribution of E > 5 Mevelectrons measured on November 10 by McIlwain on Explorer XV is shown in Fig. |2. The remains of the Starfish belt below L = 1.7 is clearly present as well as the Soviet artificial belt at L = 1.8. The E > 5 MeV flux existing out to L = 4 is probably due mostly to the Soviet explosions with maybe some left over from Starfish.



There are not thought to be any E > 5 Mev electrons in the natural Van Allen belt so this Fig.  $^{/2}$  is probably all made up of electrons from the several explosions.

#### Changes of the Electron Energy Spectrum with L

From the Soviet explosion of Oct. 28 the electron spectrum is a fission spectrum for L = 1.8 but the energy spectrum gets consistently softer with increasing L. (34) Why does the energy spectrum change with altitude? It might be due to a combination of two different sources of particles with different spatial distributions, but this seems unlikely. We have no good idea what the second electron source would be. There are two reasons why the electrons from fission decay might have different energies at different locations.

#### (a) Time after fission.

The equilibrium fission energy spectrum shown in Fig. & Curve A is the electron spectrum from a reactor but this is actually a composite of a variety of energy spectra at different times after the fission event. High energy electrons are given off earlier after fission. Fig. 3 shows how the energy spectrum changes with time after fission. (42) experimental data on the Soviet Oct. 28 explosion it would appear that it would be necessary to have fission fragments remain in space for several hours in order to get the required spectral softening at L = 1.57. This seems like a very long time but it is not impossible. Colgate (6) has suggested that most of the fission fragments from the explosion may be slowed down by the expanding debris picking up air. In this way the fission fragments may become slow enough so that  $\beta$ -spectrum will change some but I consider it unlikely that they will stay aloft for an hour.

#### (b) Particle cooling in an expanding bubble

If the electrons are confined in a bubble in the magnetic field and if the bubble expands the particles will lose energy by colliding with the receding wall.

We can calculate the slowing down of the fast electrons in an expanding bubble as a form of Fermi acceleration. (13,14)

Starting with a particle of energy E in the bubble we can study the reflection of the particle at the bubble wall by Lorentz transforming to the system in which the wall is at rest (denoted by E', p')

The reflection from the stationary wall keeps the energy constant and reverses the momentum. Now transforming back to the laboratory

$$E'' = -\beta x p' c + x E' = -\beta x (xpc - \beta x E) + x (-\beta xpc + x E)$$

$$= -2 \beta x^{2}pc + x^{2}(1+\beta^{2}) E$$

$$= -2 \beta x^{2}\beta^{*}E + x^{2}(1+\beta^{2}) E$$

where  $\beta^*c$  is the velocity of the electron and  $\beta c$  is the wall velocity, and we have used  $pc = \beta^*E$ . The fractional energy loss per collision is

$$f = \frac{E'' - E}{E} = -2\beta x^{2} \beta^{*} + x^{2} (1 + \beta^{2}) - 1$$

For fission electron  $\beta^* \approx 1$  so

The number of collisions a particle has per second with the wall is  $\sqrt{\sim \frac{\zeta}{\sqrt{1 + \zeta}}}$ 

where & is the bubble diameter. The rate of energy loss of a particle is

$$\frac{dE}{dt} = Ef_n = -\frac{2\beta Ec}{l}, \quad \frac{dE}{E} = -\frac{ll}{l}$$

which integrates to  $\frac{E}{E_0} = \frac{l_0}{l}$ 

where  $\mathbf{E}_{\mathbf{o}}$  and  $\hat{\mathbf{y}}_{\mathbf{o}}$  are the initial particle energy and bubble radius.

Now considering a distribution of energies

$$N(E_0) dE_0 = N(E) dE \left(\frac{dE_0}{dE}\right)$$

$$= \frac{1}{l_0} N\left(\frac{l_0}{l}E_0\right) dE$$

This expression, which shows how an initial energy spectrum will change as the bubble expands, is plotted in Fig. for an initial fission energy spectrum. From this we see that for a bubble expansion ratio  $\frac{1}{100} = 2$  the spectrum will soften to match the observations at L = 1.57.



For the Soviet explosion of Oct. 28 conducted roughly at L = 1.8 to produce electrons on the L = 3.0 line a bubble would have to expand at least 1600 km sidoways or more in other directions. During the bubble expansion of a factor of 2 starting from  $\lambda_0$  of several hundred kilometers the trapped particles will hit the bubble walls about  $10^3$  times. What fraction of the electrons will escape from the bubble during the expansions? If a particle scatters into the loss cone at the end of the bubble it will leak out. If the reflections at the wall are like diffuse scattering the bubble will probably be empty after 1000 collisions with the wall. But for specular reflections some reasonable fraction of the particles should stay in the bubble.

Oct. 28 explosion is interesting. There are clearly two peaks in the flux distribution versus L. (40,41) It may be that the lower flux peak at L~1.8 is due to electrons from fission fragments that have been trapped on the field lines close to the explosion and that the other peak is due to electrons released from a bubble that has expanded upwards from the explosion site. If this is the case it would appear that Fermi deceleration of particles in the bubble is the process responsible for changing the electrons' energies. It would not appear that expansion of neutral fission fragments from the explosion site and subsequent & -decay could explain the double-peaked flux distribution easily.

The observations on the energy spectrum from the USSR Oct. 28 explosion help in understanding the Starfish electron flux. The energy spectrum softens with increasing L for the Boviet explosion. Whatever the explanation of this effect is, it seems reasonable to assume that the same effect will be present for all large high-altitude nuclear explosions. Therefore we expect to find lower energy electrons at large L values in the radiation belt made by Starfish as we do experimentally.

#### Decay of the Electrons

One of the most interesting features of the Starfish artificial radiation belt has been its decay. Instruments on several satellites have observed the particle population for several months and certain general features of the decay have been found. At low altitudes the decay is rapid due to interactions with the atmosphere. At high altitudes the decay is quite fast too, but for a different reason. The atmosphere clearly is not responsible for this loss. In a region in between these two rapid decay zones the decay is slow but seems to be controlled by the thin atmosphere at high altitudes.

Before the advent of these explosions the only methods of estimating electron lifetimes were indirect. In dealing with a steady state situation where the particle population is moderately constant with time, the only way to measure the lifetime, \(\gamma\), of a trapped particle is by measuring either I, the inflow, or 0, the outflow, of particles from the radiation belt and to use the "leaking bucket" equation

$$I = 0 = \frac{Q}{2}$$

or some similar procedure. Here Q is the total number of particles trapped in the volume of the belt association with the inflow, I, or outflow, O. In the past, the values obtained this way have involved estimates of the outflow, O, down into the atmosphere and have produced widely different values of T. We now have direct measurements of T from the decay of the artificial radiation belts which eliminate the necessity of using this indirect method, which is suspect anyway.

(37)

In discussing the decay of the Starfish electrons it is appropriate to split the problem into two parts - one for high altitude and one for low altitude.

# L<1.7

In this region of space there is a rapid initial decay at low altitudes followed by a slow decay afterwards due to coulomb scattering with atmospheric atoms. Van Allen, Frank and O'Brien measured the decay of the artificial electrons at 1000 km with the Injun satellites. This is shown in Fig. 14. After the initial rapid decay which is larger for large B values (or low altitude) the decay slows down and is nearly constant for all B values. Measurements on Alouette firom Sept 1912 to Jan 1963 of the decay of the Starfish electrons (31) gave time constants of several months for the region 13 < 1 < 16. McIlwain studied the trapped Starfish electrons on Explorer XV for about three months starting in Oct. 1962. He found that for 1.25 < L < 1.7 the decay constants were typically greater than one year and in some cases are more than three years. (3%) At lower altitudes the decay is faster. Glass (76) has

At lower altitudes the decay is faster. Glass has measured the electron decay at 400 km and has found that the decay for several months after Starfish could be described by the law

$$\phi(t) = \frac{\phi(0)}{1 + \frac{1}{20}}$$
 where t is the time in days.

The decay of trapped electrons controlled by the atmosphere can be calculated in a traightforward way.

(17)

MacDonald and Walt have derived a Fokker-Planck equation that describes how a distribution of electrons in space and energy will change with time as the result of coulomb scattering. This has been used by Welch, Kaufmann and Hess to study electron time histories.

Neglecting cross field diffusion and neglecting large angle scattering the time change of a distribution of electrons, U, in space and energy is obtained by using the Fokker-Planck equation

The distribution function U is defined as the number of particles at time t in a magnetic flux tube of flux dF and mirroring in the magnetic field interval dB at B and having energies in d x at x, where x is the relativistic dimensionless energy  $x = \frac{E}{W} \frac{E}{x^2}$ 

The terms in the < > above are the time rates of change of the quantities involved which result from atmospheric coulomb scattering. The atmospheric model used in the calculation is that of Harris and Priester near solar minimum. The atmosphere is averaged over local time and also averaged over longitude considering that a particle's mirror point changes altitude as the particle drifts in longitude.

(3)

The < >terms are evaluated using small angle coulomb scattering. A tube of force is Urchan up into 100 space cells of equal riangle B and the fission energy spectrum used was broken up into 9 regions of A of about .75 Mev each. For a starting condition U was taken to be constant all along a field line. Then the problem was run on a computer to watch the distribution change in time. The results of such a calculation are shown in Fig. 5. The electrons at large B (or low altitude) are lost first and as time progresses the particles nearer the equator are lost. Eventually an equilibrium develops where scattering up the tube of force is balanced by scattering down the tube so that the spatial distribution stays constant and the whole distribution then decays in time maintaining its shape. For this equilibrium the decay rate is controlled by the rate of scattering at the equator and is therefore slow compared to the initial decay at low altitudes. The comparison with the experimental data from Injun on Fig. 15 shows that the calculation removes: particles at large B faster than it should. Recent changes in the Harris and Priester model atmosphere increasing the He density should make the agreement better. The decay rates given by the calculation agree reasonably well with the experimental data. The variation of decay constants with altitude and also the change of ? with time (as indicated by the changes from Alouette T's to McIlwain's T's in the same region but at different times) is in agreement with theoretical expectations.

The decay for carly times can be expressed approximately as

where \(\gamma(B)\) is a characteristic decay time. This decay law gradually merges into an exponential decay as scattering equilibrium is reached.

The decay represented in Fig. is what is expected for the atmosphere near solar minimum and will probably be reasonably good for the next year or so. But as solar activity picks up and we get close to solar maximum, the decay will increase very markedly. A large fraction of the Starfish electrons still trapped now will be lost before solar maximum.

During theprocess of atmospheric scattering, the electron energy spectrum changes. The lower energy electrons are more easily scattered and therefore lost first. Because of this the fission energy spectrum hardens with time until and equilibrium spectrum is developed with a peak at about 2 Mev. The Fokker-Planck calculations show this process develop as in Fig. 6.

The spectrometer flown on 1962 \$K\$ measured an electron energy spectrum at L = 1.25 (see Fig. 8 curve 3 ) in December 1962 which is quite similar to the calculated hardened fission spectrum in Fig.// curve G . From a comparison of the several detectors aloft (26) at early times after Starfish the spectrum seemed fission-like down

to  $\frac{1}{2}$  MeV at L = 1.25. Therefore the lack of low energy particles in the L = 1.25 spectrum in December is not due to an initial paucity of them but rather to a loss of them after they were trapped. This is what is expected from coulomb scattering.

An electron spectrometer (33) flown on another Air Force satellite in September 1962 measured an energy spectrum quite similar to curve 5 in Fig. 7 for 1.2 < L < 1.6 confirming the emistance of a hardened fission spectrum.

## L > 1.7

The situation is quite different for L>1.7. Brown and Gabbe measured on Telstar the decay of the transient electron population introduced into space by the Starfish explosion. They found the decay curves in Fig. [7] for L>1.7. In this region of space the electron population decays with short time constants. At L = 1.7 the decay constant is many months but by L = 2.2  $\gamma \approx 1$  week. It seems impossible for this rapid decay to be due to the atmosphere. It is very likely due to some kind of magnetic disturbances which breaks down one of the adiabatic invarients. Although there are several ideas about the types of disturbances involved (50,51) real nature of this process is not known.

Measurements made after the three USSR explosions for L > 1.7 give decay constants quite similar to the earlier Telstar data. McIlwain (38) on Explorer MV found the decay was quite steady and monotonic for L  $\approx$  3, after November 1.

But for Lesh the decay is quite different. There are several stepwise decreases in the flux apparently related to magnetic storms. On Dec. 18 a large increase in the electron flux occurred at the time of a new magnetic storm. The increase of the E 5 Mev electrons at this time was more than a factor of 10 and made the flux roughly what it was shortly after the USSR emplosions. This increase looks suspiciously like particle asceleration. Electrons of E 5 Mev are not thought to exist in the natural belt so it would appear that this change on Dec. 18 was due to acceleration of particles already there rather than to injection of new particles.

Measurements on Teletar (39) after the USBR explosions also show the rapid decay of these new electrons for L 1.7. By studying the time decay of the Starfish electrons we have learned a considerable amount about the natural radiation belt. We know that electrons in the inner zone of the natural Van Allen belt have long lifetimes and those in the outer sone have short lifetimes. This information would have been very difficult, if not impossible to obtain, by observing only the steady state natural radiation belt. This is a very important contribution to our understanding of the radiation belts.

What we have learned from Starfish shows that there is much that can be accomplished by carrying out controlled charged particle-injection experiments in space by nuclear emplosions or by using radicactive isotopes or small purticle accolerators. Experiments are possible on the

production of artificial aurorae, artificial VLF disturbances, artificial ionospheric disturbances and related upper atmospheric chemical processes. Also more work is needed in trapped particle lifetimes, acceleration and loss processes. This should be an important field of future experimentation.

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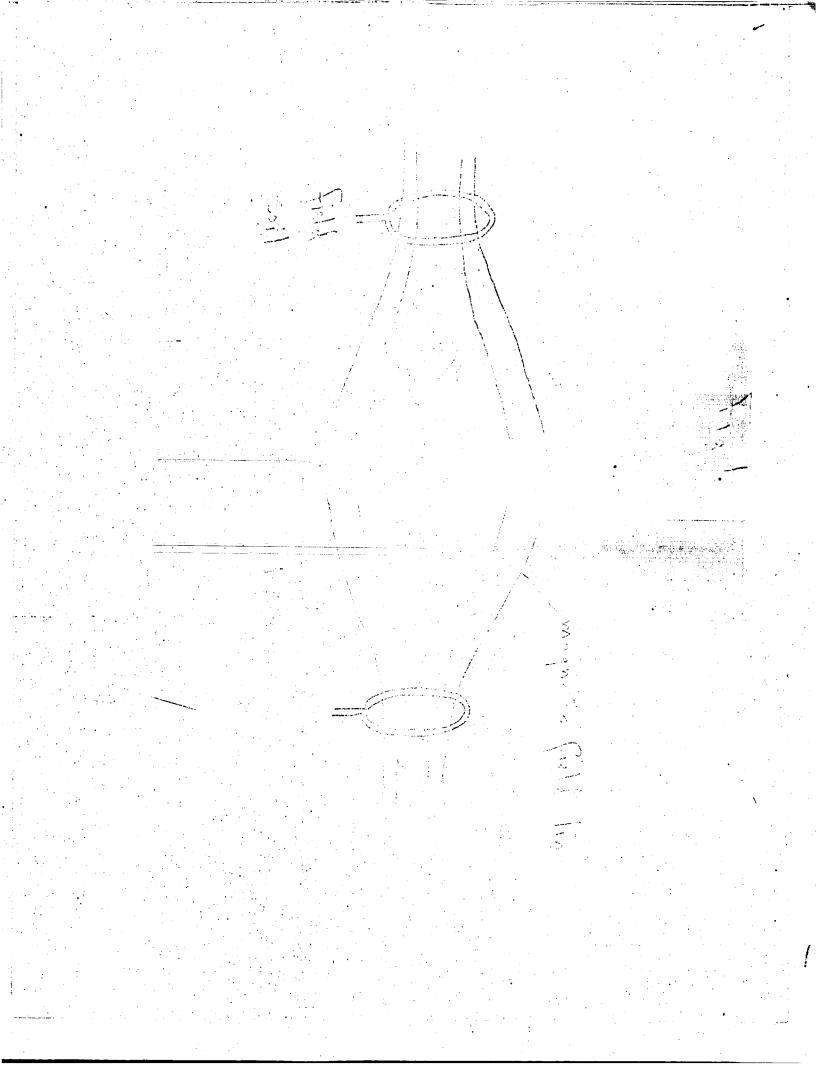
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- (B) E>1,9 May Oct. 28 at ~ 0900 teT
- (c) E>.5NwOct. 28 at ~ 0400 wy
- (D) E>. 5 Now Oct. 28 at ~ 0900 tr (from Reference 40)
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17. Time decay of the Starfish electron flux for L>1.7 measured on Telstar. (from Reference 39)



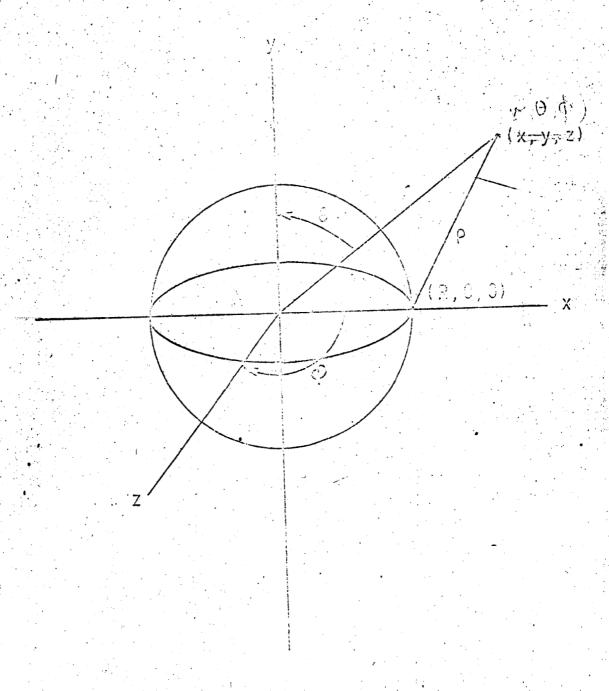
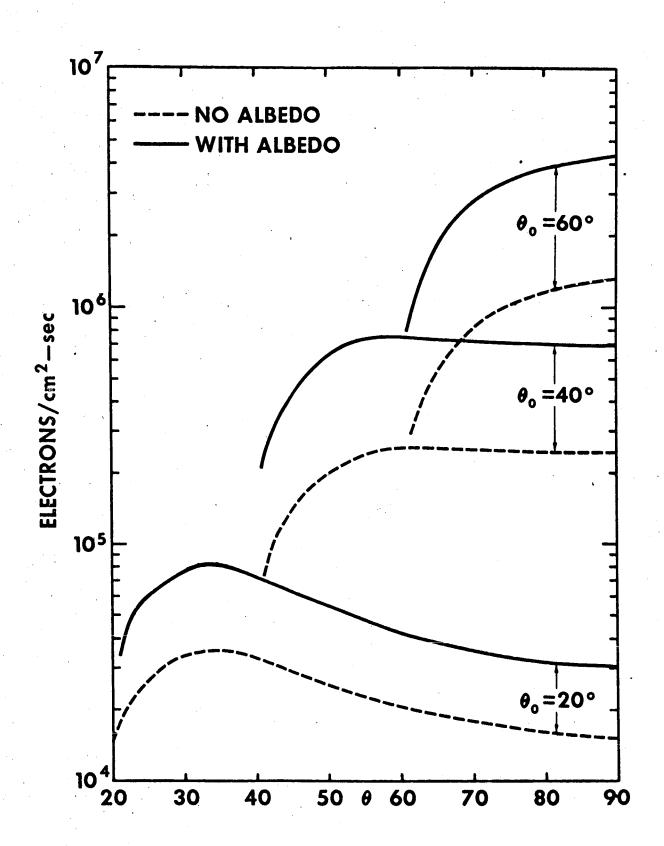
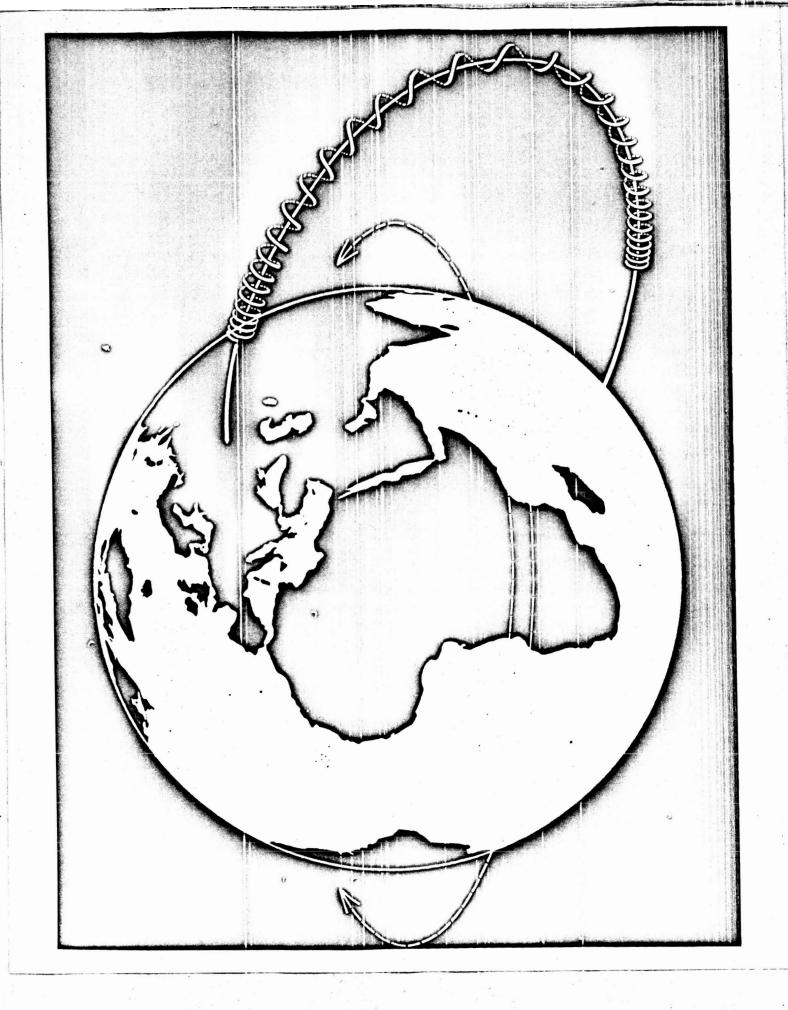


Figure 2

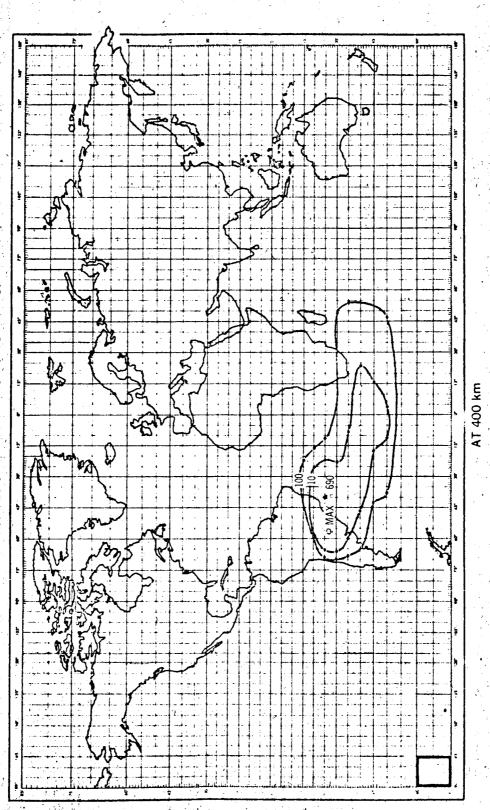




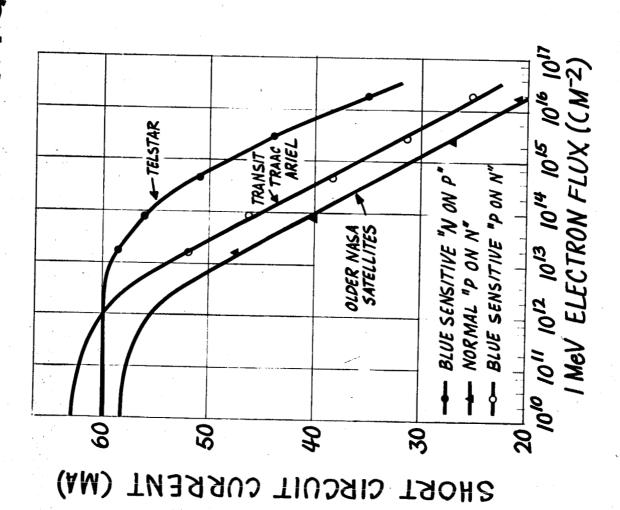
X X X × XX xxxx XXXX x x x × ×××× XXXX X XXX XXXX xx kx X X × XX X X X: X XXXX الله المالة XXXX XXXX magnetic ( x x x x × × × × XXXX XXXX XX XXX × × × ×

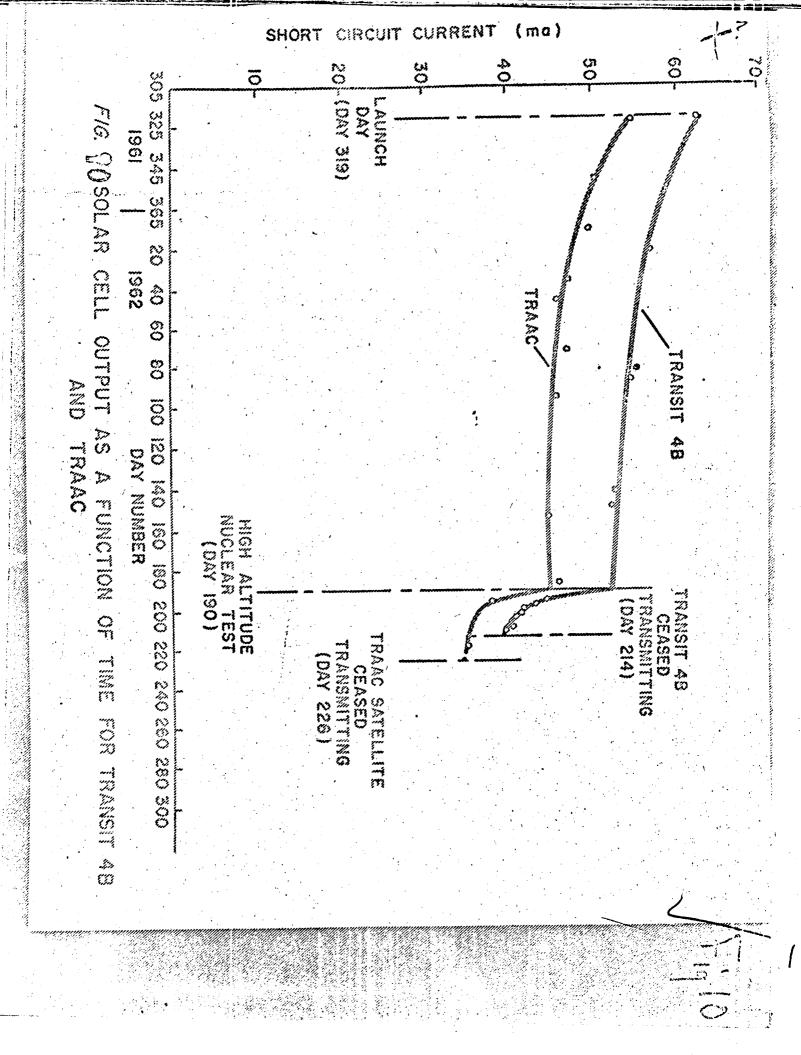
# COMPARISON OF INJUN & TELSTAR CONTOURS



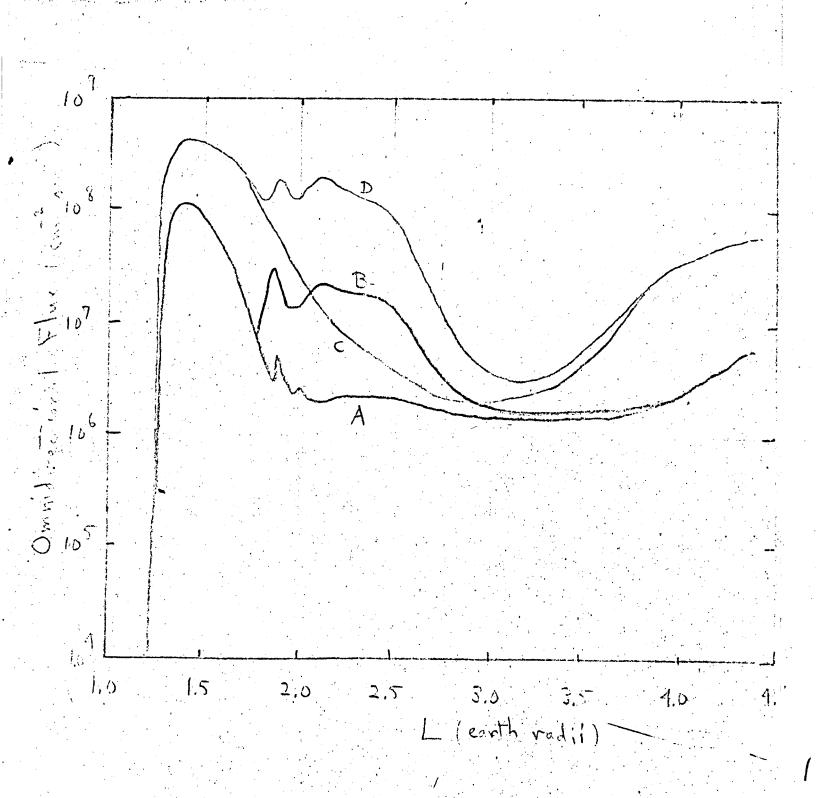


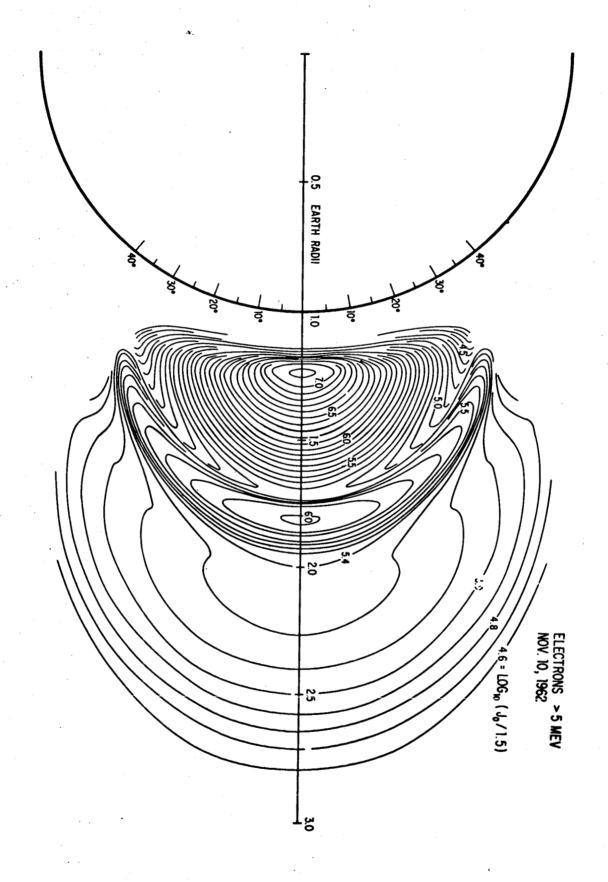
# SOLAR CELL DAMAGE





Figl





<u>i</u> . . .

3. 1

SCYCLES X 70 DIVISIONS

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